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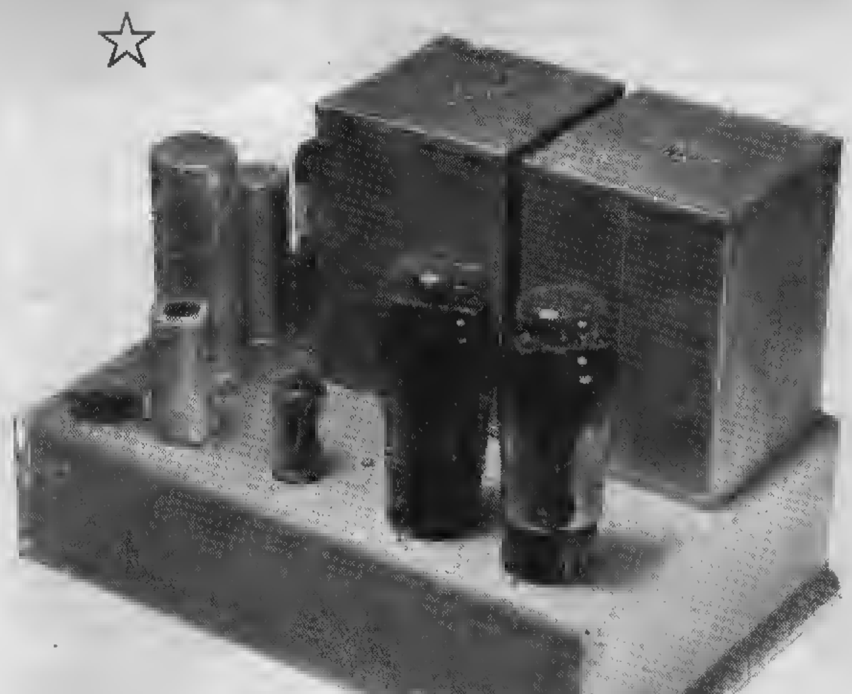


One of the Playmasters used for tests described in the article. The second version, with similar performance, used a different make of output transformer, but obviously we cannot picture them all.

Amplifier Response Stability & All That

This article discusses the effects of the output transformer on some aspects of amplifier performance with particular reference to high frequency stability. It deals mainly with practical results, and includes the evidence of tests made with typical commercial designs and one of our own.

by John Moyle

PERHAPS the most puzzling thing about amplifiers, at least to the man who wants one, is the very great discrepancy in the behaviour and specifications of many designs, all of which may be good, and the product of well-informed engineers.

In the matter of power output there is not a great deal of difficulty, for, although there are differences of opinion as to how much power is needed for home use, the user of an amplifier can please himself about the amount of power he elects to use.

But in many other matters he may well wonder just where he stands.

Frequency response is perhaps the one single specification where great variation can be seen. Some amplifiers with famous names commence their high frequency attenuation as low as 10 kc, with a 3 db loss at perhaps 25 or 30 kc. Others run well over the 100 kc mark before this point is reached. Some very few will exceed even this figure—we have made them ourselves.

Distortion, too, varies a great deal if we can believe the data sheets. Most of the better type will claim down to .1 per cent at substantially full output, and some even better. Others are satisfied with a figure higher than this.

Some pay great attention to the amount of intermodulation distortion they are able to quote—others leave it out altogether.

Then there is the matter of stability, about which nearly all amplifier specifications are dumb. Sometimes we find statements that a certain design will stand an extra 6 db feedback without oscillation, and some such figure is given as a stability margin. Very few will specify the conditions under which such a test would be made, which detracts almost wholly from its value.

How is it, then, that with the same object in view—a performance which can be considered more that adequate for the reproduction of music—ideas and results vary so greatly?

An obvious conclusion which can be gleaned from all this is that there are no recognised standards by which an amplifier can be judged.

It is true that many tests have been made by those interested in the field to determine how much distortion can be considered permissible in listening tests, but even these do not agree. Moreover, they are all the more difficult to rationalise because they depend greatly on the type of input used, whether simple or complex wave-form, the frequency response of the equipment, the age and even sex of the listeners and so on.

And it's a horrible truth that some amplifiers which do not produce the very best figures sound very well indeed: virtually indistinguishable from others which show very much better test results.

BEST DESIGN

We can't seriously disagree with the idea that the design which has the flattest frequency response, the lowest distortion, the most uniform power curve, the highest degree of stability and so forth will be the best amplifier, even if its results are patently beyond those even the most fastidious could require for use with gramophone records.

But, how much poorer could such an amplifier have been in its various qualities before the listener would detect a difference? That's the heart of the matter as far as the user is concerned.

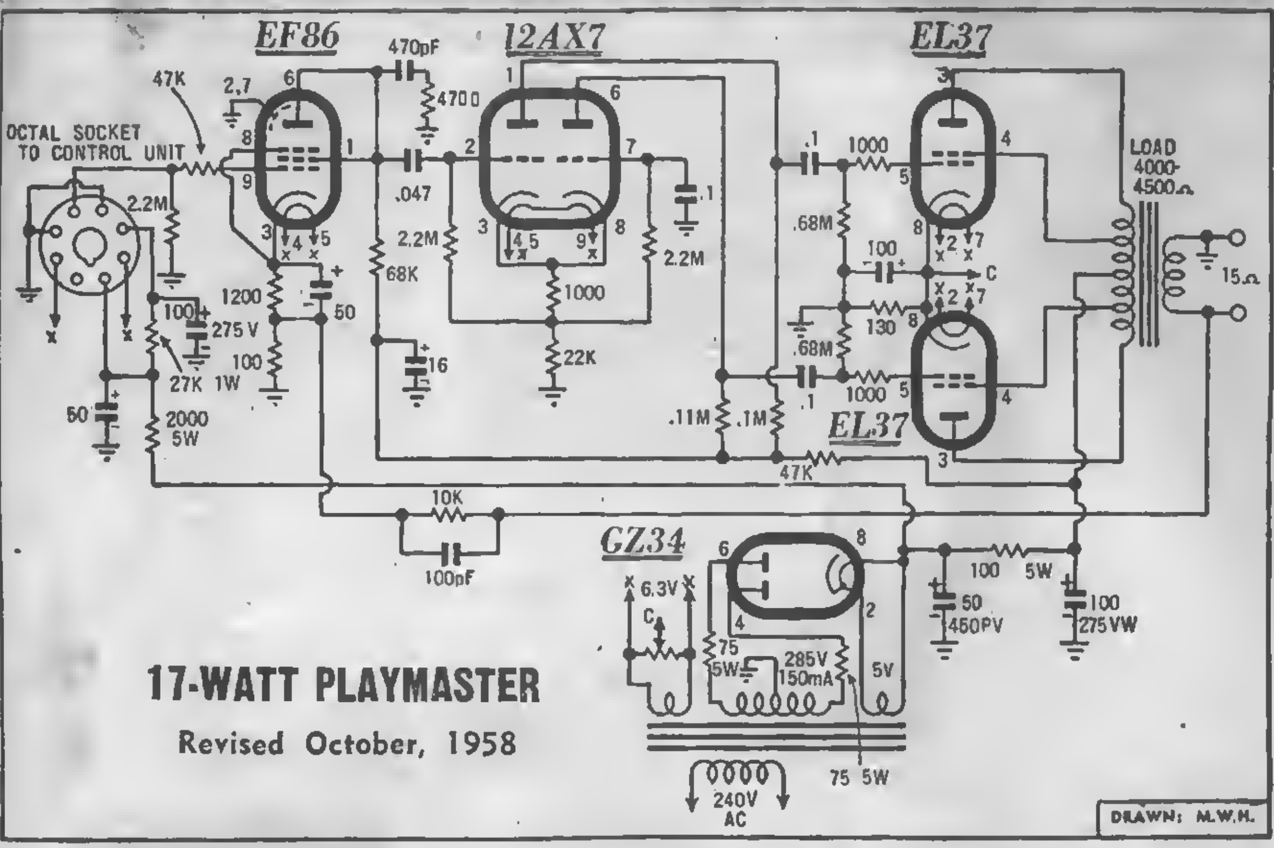
Without doubt, if cost is no object, the designer's work is made very much easier. If a high-priced outfit is able to boast of supersonic specifications, we can't blame the manufacturer for claiming them. Nor can we blame his competitor for trying to do equally well even if he has to sacrifice some desirable feature to achieve another which looks more impressive on paper.

The man who has a cheaper and less spectacular unit for sale, may well wring his hands, particularly as he often knows that the listener might not be able to distinguish between his product and one much more costly.

One of the difficulties we face when trying to be specific about these matters is the lack of exact knowledge about the nature of the input our entire system is expected to handle. And, in this respect, the nature of anticipated transients is as obscure as any.

In checking amplifiers, a squared wave at 5 kc is often accepted as an excellent thing to test the behaviour in the high frequency region, mainly because its sharp, vertical component is well suited to demonstrating performance under the attack of sharp wave-fronts, and because

PLAYMASTER MODIFIED FOR EXTREME STABILITY



The 17-watt circuit showing addition of step circuit. It is not essential to stability on any form of normal loading. The grid stopper is a precautionary addition, found necessary only when test leads were connected and the critical capacitance added to the load — a condition most unlikely in actual use as our test wave forms demonstrate.

it shows up probably better than any other method the degree of ringing and overshoot suffered by the amplifier.

Most such square waves have a very sharp wavefront, representing a rise time in voltage from zero to maximum of perhaps one microsecond, or even less. The application of such a wave-form with a 5 kc fundamental is a very severe test.

It is virtually certain, however, that no input we are likely to use in practice can possibly include such a fast rise-time. We are not immediately concerned with the characteristics of the wavefront as it exists in nature, for, even supposing there were sounds generated having this characteristic, they would suffer very considerable attenuation before the amplifier eventually received them.

RECORDING PROCESS

The very process of recording means that the wave-form must pass firstly through a considerable amount of air, which will be responsible for appreciable attenuation of such wavefronts, even over comparatively short distance. Then we have a microphone, numerous amplifier stages, an entire recording and reproducing system with tape, more amplifiers, a cutting head, and, finally, a record manufacturing process with many stamping cycles. Finally there is a pick-up and a set of loudspeakers.

If the tape itself is to be played, we can eliminate some of the intermediate steps, but the damage will have probably been done long before this.

If we relate the probable fastest rise time to these matters, and the frequency response of the system, we might estimate a rise time of 30 microseconds as being a very good standard.

Recording engineers are not very helpful when asked to confirm such figures, which is understandable because it would be a very difficult task to perform with any degree of accuracy.

Perhaps it is fortunate that we can frequently make amplifiers which test very well under our severe conditions, and we can't deny that they are more likely to give good results than those that do not show up so favourably.

In effect, this principle seems to be the basis upon which the average amplifier designer operates. Knowing the amount of money which can be spent by the factory, he collects together all the desirable things he would like to achieve, and then does his best.

And, when surveying what these results are likely to be, it is obvious that by far the most vital component of all is the output transformer.

The almost universal use of transformer coupling is fairly solid evidence that it provides the most useful method of coupling the output valves to the loud speaker. There is a considerable impedance difference existing between these two essentials, and although circuits have been devised and used more or less successfully which avoid the transformer, they have difficulties of their own which in most cases outweigh their advantages.

And the fact is that it is possible to make very good output transformers, more than adequate for the work they are called upon to do.

Nevertheless, while we use transformers, we must be aware of their characteristics and how they affect amplifier performance.

The main points in which we are vitally interested concerning transformers are their influence on frequency response, power output at various frequencies, and, in feedback circuits which are now universal, stability and freedom from oscillation.

There are other points to be considered, of course, such as distortion, and it is true to say that all such factors must be considered together when working on design.

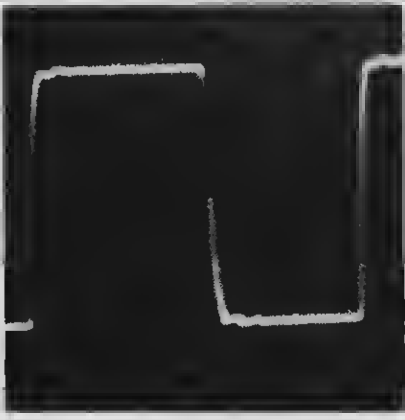
All these points are also affected by amplifier circuit design, but in the process of development and experiment, all the standard types of amplifier circuits in common use give roughly equivalent results, at least until the finer points of performance are concerned.

AVERAGE CIRCUIT

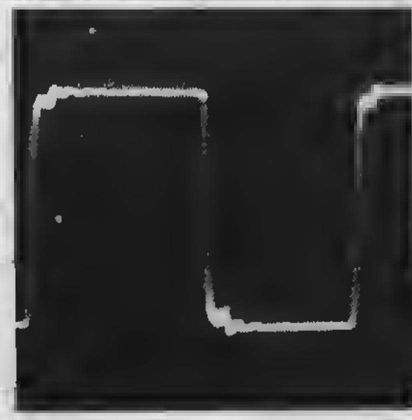
The average amplifier of today has three stages — a voltage amplifier, either a pentode or a triode, a phase changer, either the plate cathode type or some version of cathode coupling (a few use paraphase circuits) and a push-pull output stage with an ultra-linear connection. In most of the good quality amplifiers we have tested, little performance variation could be traced to circuitry.

Provided the valves are operated in the

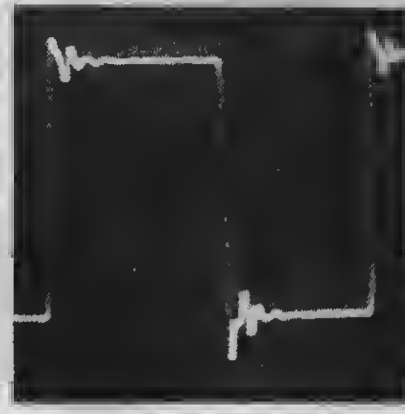
TEST WAVEFORMS OF COMMERCIAL AMPLIFIERS



Amplifier No. 3 on 15 ohm resistive load. Not bad, but ringing extends along vertical line, a suspect condition.



Amplifier No. 1, on 15 ohm resistive load. Multiple ringing well damped with rounded corners.



Amplifier No. 1 on open circuit. Ringing and overshoot have noticeably increased but under control.

most linear fashion practicable, are not required to deliver output beyond the maker's ratings for low distortion or otherwise abused, their total contribution to distortion is well under control.

The transformer itself also contributes a small amount of distortion, but the fact that the overall figures given by an intelligent hook-up are very small, is enough for us to leave the question at this point, except as it is affected by other considerations in which we are interested at the moment.

The almost universal practice of including the output transformer in a negative feedback loop referred back to the input circuit is the most effective way of dealing with over-all distortion, for with an easily obtainable 20 db of feedback, distortion is reduced to about one-tenth of its previous value. It is the most helpful factor in dealing with all kinds of distortion generated within the amplifier.

It is also almost entirely responsible for the frequency response and stability of the amplifier, and mainly through these two, the square wave performance or transient characteristics as well.

POWER OUTPUT

The amount of power obtainable from the transformer at low frequencies depends primarily upon the amount and grade of iron used for the core. The lowest frequency which will be reproduced without loss is a function of the inductance of the primary winding as referred to the output load required by the valves. Because the transformers' size must be reasonable, there will be a falling off in both power handling and frequency response beyond some given point, and a natural droop in the transformer curve.

At the high frequency end there will also be a drop in frequency response due mainly to the self-capacitance of the windings which acts as a high frequency bypass and inefficient coupling between windings. This attenuation can commence well within the limits of audible response unless great care is taken to minimise both sources of loss. Sectionalised winding is the universal method of doing this, but, even so, all transformers will behave in this manner.

As such, the frequency response of the amplifier would be very poor by modern standards without the application of negative feedback.

Negative feedback is a gain-reducing connection, and, because the amount of feedback will depend on the amplification of the amplifier at any frequency, it will be least at frequencies where the gain is lowest.

EFECT OF FEEDBACK

If, for instance, we have 20 db of feedback at 1 kc, we will have a gain reduction of 10 times at this point.

But if we select a frequency at which the amplification without feedback is only half of that at 1 kc, the feedback will also be halved, and the over-all amplification reduced by only 5 times.

We can thus consider feedback to act as an automatic gain control, and the more of it we use the more will it flatten out a response which originally drooped at both the high and low end of the spectrum.

Were it not for other factors which raise their ugly heads as we pile on the feedback, there would be virtually no end to the process, and quite poor transformers would give very flat responses so long as the initial drop in over-all gain could be accepted in the design.

It would be most convenient if output transformers were to fall smoothly away at each end of the frequency range, but they do not. Particularly at the top end we find peaks and troughs developing in the response as feedback is increased, and, at some stage, the amplifier will oscillate, the frequency of oscillation being at some point almost always outside the audible frequency band.

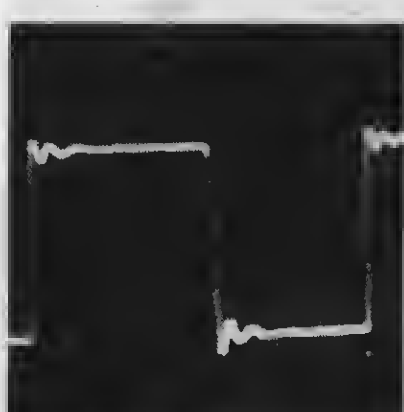
According to the transformer characteristics it might be anywhere between about 30 kc and 500 kc.

The oscillation is due to a change in the phase relationship between the input voltage and the feedback voltage. Ideally this should be completely negative all the time, which means a phase difference of 180 degrees.

OSCILLATION DANGER

But, if a response peak should appear in the curve, instead of a negative feedback at this point it is possible to have a positive feedback. When this happens, we have not degeneration, but regeneration, and consequently oscillation or the danger of oscillation.

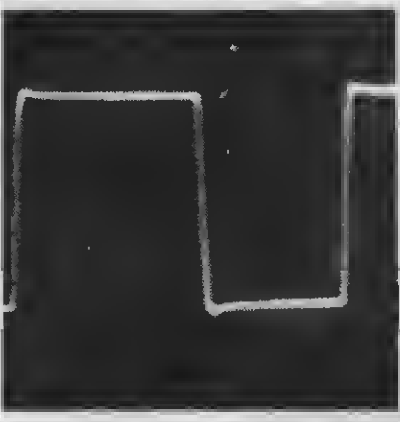
Two points should be remembered here. The frequency and amplitude at which these peaks occur is largely governed by transformer characteristics. Feedback does not materially alter their frequency, but it increases their ampli-



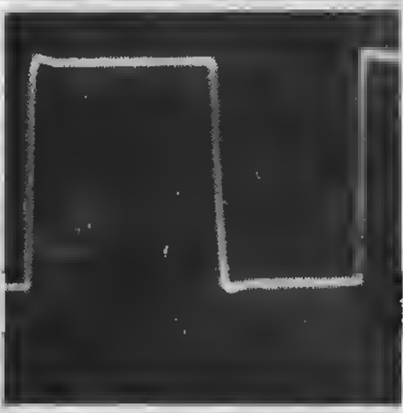
Amplifier No. 4 on 15 ohm resistive load. Ringing is pronounced and regular in frequency.

Amplifier No. 4 on open circuit. Ringing is less but overshoot peak emerges. Load capacitance would increase this.

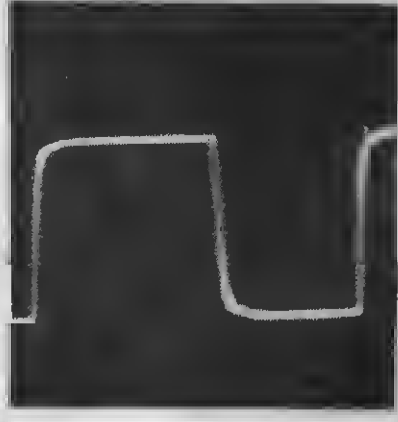
TEST WAVEFORMS OF 17W PLAYMASTER CIRCUIT



Playmaster with 3 section crossover, indistinguishable from waveform on 15 ohm resistive load. Negligible ringing



Playmaster on open circuit. Almost identical with that of previous photograph.



Playmaster on 2 ohm resistive load. Even on this extreme waveform is still free from major faults.

tude very greatly, for it is at these points that feedback is lessened because of the positive-moving phase shift. The more feedback we apply the higher the gain will rise at these resonant peaks, where feedback may be removed altogether.

What causes these peaks in transformer response?

They are caused by a resonant circuit or circuits consisting of the self capacitance and leakage inductance of the windings or even sections of the windings (an inductance representing coupling losses between primary and secondary). These resonances generally occur at response points where, without feedback, the amplifier gain has fallen considerably due to transformer limitations, and they will not cause oscillation unless some unscheduled feedback paths exist. But in an amplifier with negative feedback, we have ourselves provided the means by which undesirable phase relationships may take place, and oscillation will occur as soon as the peaks become sharp enough unless steps are taken to avoid it.

TRANSFORMER TYPES

If the transformer is of the simple type, with few winding sections, and comparatively loose coupling between primary and secondary, a resonance peak may be found at one frequency only, of high amplitude, and probably about 50 kc.

In a more elaborate transformer, with many sections, and more efficient coupling, it is probable that more than one peak will be in evidence, at frequencies varying from 150 kc to 300 kc, and of considerably lower amplitude. However, there is no general rule about this —the control of resonances is part of the manufacturer's art, and transformers vary so much in characteristics that it is almost impossible to set circuit values which will give optimum performance from them all.

As a general rule, transformers with a high amplitude peak anywhere in their response curves can only be used with limited amounts of feedback without oscillation. Corrective methods inevitably degrade both frequency and square-wave response, but generally speaking it is best to move the peaks as high as possible and to keep their amplitude low. This means that corrective measures need concern only that portion of the response above the point at which they commence, and with a good transformer this can be as high as several hundred kilocycles.

Nevertheless, with large amounts of feedback, we cannot be certain of complete stability without loss beyond about 50 kc, even with transformer peaks which occur far beyond that point.

CORRECTION METHODS

So complex is the calculation of transformer design of this nature, particularly as cost and manufacturing processes must be considered, that most units are the result as much of experiment as of mathematics.

This is also true of the corrective methods which can be used, and the manner of their application. It is possible to forecast them only within certain broad limits — beyond these individual adjustment is the only certain method without a certain amount of brute force.

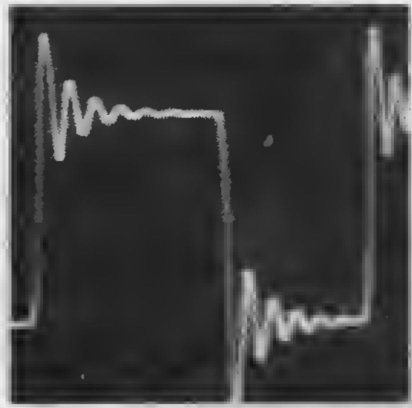
For this reason, amplifiers which use feedback of the order of 20 db or even more, inevitably use correction methods quite freely, and quite often exhibit the poorest frequency and square wave characteristics.

However, these are generally still well within what we may consider high limiting standards—which is where we came in!

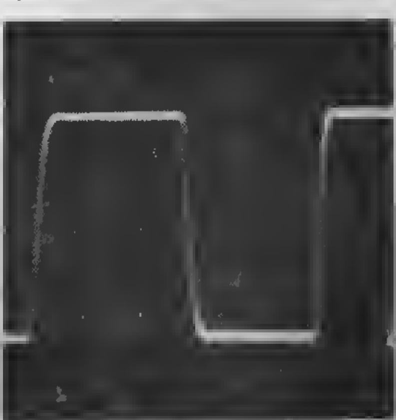
A stable amplifier is not merely one which does not exhibit continuous oscillation. Any resonant condition, if not corrected, will cause "ringing" or damped oscillations over portion of the audio cycle if excited at or near its resonant frequency. Square wave tests to simulate input signals with steep wave fronts are very useful to detect this condition, which will show up as a damped oscillation on the flat top of the waveform. Nearly all amplifiers will ring to some degree even when corrected, and this is not particularly significant provided the ringing amplitude and duration are small.

USE OF SQUARE WAVES

Steep-front square waves will generally show up the ringing to best advantage because the frequency components of such a wave include very high frequencies likely to be at least equal to and probably higher than the resonance frequency. If more than one resonance is present, the ringing will have an irregular periodicity; if one resonance peak predominates it will probably swamp the others and show up as a regular superimposition. By observing the ringing characteristics, a great deal can be learned about the transformer resonance, and this information can be cross checked by a frequency run of the amplifier to observe the various peaks the



Playmaster with crossover and added .5 mfd capacitor. Note how this induces ringing on otherwise excellent waveform but as yet no instability.



Playmaster with 10Kc square wave and cross-over network. Virtually the same as with 5 kc as used with remainder of photographs. Slope of verticals mostly due to the generator and CRO.

result of which is displayed by the square wave method.

There are two standard methods of correction applied to amplifiers to improve stability and reduce ringing.

Because the presence of a resonance peak is due primarily to removal or reduction of feedback as a result of positive going phase change, a capacitor across the feedback resistor normally connected from the voice coil circuit to the input of the amplifier can be selected to modify the feedback at the resonance point and beyond.

The effect of this capacitor is quite dramatic in its results.

It is most effective when a single resonance peak predominates, and will often remove a pronounced ringing condition to little more than a small wriggle at the commencement of the square wave trace.

It can be fixed also by first locating the frequency at which the peak occurs, and selecting a value which removes or greatly reduces the response peak.

Almost invariably the two methods will cross check.

It is obviously not practicable to "phase out" more than one peak by this method, unless there are several quite closely spaced. This is generally not the case, but fortunately the others will be of a small amplitude in a good transformer.

Nevertheless they can be sufficient to cause positive feedback if large amounts of feedback are used, or if we insist on testing for stability under every conceivable load condition, each one of which will vary the characteristics of the feedback circuit because of its intimate connection to the voice coil, itself a sensitive point in the feedback loop.

USE OF ROLL-OFF

If this should be the case, the only easy additional method, having done what may be done to vary the feedback factor, is to alter the rate of amplifier attentuation or "roll-off" by means of a capacitor to ground, usually wired at the plate of the first valve in the amplifier.

This method will so reduce amplification in the region of danger that neither amplifier gain nor feedback is significantly high enough to cause trouble.

If the amplifier has a single resonance peak fairly low in its range — between 100 and 200 kc for instance, a simple capacitance to ground will probably be sufficient.

And because the presence of this capacitor also affects the feedback at this point, it will be necessary to revaluate the capacitor across the feedback resistor for best results.

But if the amplifier initially has a very wide bandwidth — significant up to 300 or 400 kc as can happen, a step circuit wil probably be best to attenuate the response in the danger region, and allow it to flatten out again at the extreme top end.

A combination of these two methods will probably produce the maximum of stability together with the widest response.

If the amplifier should not be amenable to delicate placement of this capacitor or step circuit, then a more severe attenuation will probably be necessary and a 3 db point at about 30 kc must be accepted.

It cannot be stressed too greatly that the foregoing represents only a general description of ways and means in popular use, and that there are almost as many variations possible as there are transformer types produced. But the pattern is there, not only in our experience, but in the observation of numerous commercial amplifiers which we have checked and examined.

It might be profitable now to set down some of the results of this process, and see if some practical application can be extracted for the guidance of those who build their own.

The first amplifier was a costly job with an output over 20 watts. Its frequency curve showed a flat response to 35 Kc, plus 2 db at 65, zero at 95, minus 2.5 db at 115, plus 3 db at 150, zero at 185, minus 3 db at 200, minus 6 db at 225 and minus 12 db at 250.

DESIGN PATTERN

It used feedback compensation and a step circuit, so that an obvious attempt had been made to control multiple resonances throughout the response, not surprising as the output transformer was more complicated than usual.

The presence of peaks and troughs in the upper response made some ringing probable, and square wave tests showed its presence to a moderate degree and with irregular periodicity.

Tested on 2 ohms, 15 ohms, 15 ohms plus capacitance and open circuit, this amplifier did not oscillate.

It was also stable on a three-section divider network with any added capacitance, although very near oscillation with an added .5 mfd as indicated by severe ringing.

The second amplifier was also a high-powered costly design, but its characteristics were quite different. It was flat up to 10 Kc where a drop of .3 db was measured. It then rolled off smoothly — .7 db at 20 Kc, 2 db at 45, 3 db at 65, 6 db at 100 and 12 db at 135 Kc.

This smooth roll-off suggested a good square wave response with probably some drop in the leading edge, which is just what was found. Otherwise the waveform had a flat top with virtually no ringing. As was again expected, it was quite stable under any kind of load as used for Amplifier No. 1.

This amplifier used correction across the feedback resistor and a small capacitance to ground from the first valve plate.

Removing the correction components revealed a large peak at about 150 Kc and considerable ringing on 5 Kc square wave. Reconnecting the plate bypass removed this peak, but provided a smaller one at about 80 Kc. The feedback correction capacitor wiped this peak, and the response was then as already indicated. An excellent example of intelligent design which, despite its comparatively early roll-off, sounds extremely good.

This amplifier was not available for the divider network test, but it would probably have been stable.

The third amplifier was lower-powered, and commenced its roll-off at 20 Kc where it was down .7 db. Then followed minus 1 db at 30 Kc, 2 db at 50 Kc, 3 db at 65 Kc, 6 db at 82 Kc, 8 db at 110 Kc, 8 db at 125 Kc, and 12 db at 250 Kc.

Although the square wave performance was quite good, with some rounding off at the leading edge, this amplifier on resistive load showed some oscillation bursts at full output below 100 cycles, and became unstable with 15 ohms resistive load plus .002 mfds. and above. This result could be suspected from the "flat spot" between 110 and 125 Kc, indicating that the transformer probably had resonance effects in this region which, despite a step circuit connected to the first amplifier valve, had not been adequately dealt with.

NOT STABLE

This amplifier oscillated on speaker load with 30ft of twin flex lead and no extra capacitance.

The fourth amplifier was also a lower powered job, flat to 10 kc but with a rise of .5 db at 20 kc, 1 db at 35 kc and 3 db at 80 kc. It fell to zero at 115, minus 3 at 150, 6 at 180 and 12 at 250 kc. It used both feedback correction and a step circuit.

The square wave showed some ringing, but on 15 ohms the amplifier was stable. It had several impedance tap-

(Continued on Page 111)

AMPLIFIER RESPONSE, STABILITY AND ALL THAT

(Continued from Page 39)

pings, and on these optional impedances it was unstable with added capacitance across the load. It also oscillated on speaker load and divider network but only with .47 mfd added. With other values it was stable on the 15 ohm connection.

All these amplifiers used between 22 and 28 db of feedback, with No. 2 having the largest amount.

By way of comparison, two versions of the 17-watt ultra-linear amplifier were subjected to the same test, the circuit being the same as that used for "My Personal Amplifier" and reproduced herewith, but with the addition of a step circuit at the plate of the first valve as suggested in a recent article, and an isolating resistor in the input grid circuit.

As the illustrations will show, the square wave shape was almost perfect. Most significant is the small change in square wave response over a wide load variation.

On a 15-ohm cross-over network, both these amplifiers were tested at various times without a step circuit, and showed no oscillation with long speaker leads.

Under these conditions one of them gave an exceptionally fine frequency response and a virtually perfect square wave, as all its resonances were small and very high in the range.

It was flat from 15 cycles to 30 kc, minus 1 db at 65 kc, 2 db at 95 kc, 3 db at 115 kc, 4 db at 145 kc, 6 db at 200 kc, 7 db at 300 kc, 9 db at 400 kc and 12 db at 500 kc.

No difference could be detected in listening tests either with or without the step circuit.

Using the step circuit, the first amplifier was flat from 15 cycles to 20 ks, minus 1 db at 48 kc, 2 db at 60 kc, 3 db at 75 kc, 6 db at 100 kc and 12 db at 165 kc after which the gradual roll-off continued. It used 22 db of feedback.

The second was flat from 15 cycles to about 30 kc, minus 1 db at 52 kc, 2 db at 3 kc, 4 db at 85 kc, 6 db at 100 kc and 12 db at 130 kc, after which roll-off continued. It used 20 db of feedback.

The only circuit difference was a 12AX7 phase-changer in the first, and a 6SL7 in the second, with feedback resistors to suit.

Both amplifiers were completely stable on any kind of resistive or speaker loading, even when feedback was increased to over 30 db. The only sensitivity to oscillation occurred when a capacitance of .047 mfds was connected directly across an inductive load. Values substantially above or below this figure, even when connected across the output on open circuit did not cause oscillation.

From these observations and tests some general conclusions can be made, particularly as they affect the matter of HF stability.

All amplifiers using voice coil feedback are sensitive to some value of pure capacitance connected across the load. This is because the voice coil circuit is part of the feedback loop, and adding capacitance is tantamount to upsetting feedback correction which the designer has been at some pains to provide. Even if no oscillation is present under this critical condition, few amplifiers have a very great margin of safety, and exhibit very severe ringing and poor transient response.

As long as the critical capacitance value is not comparable either with that of long speaker leads, or of a cross-over network, it can be neglected as a factor in practical stability. For instance the oscillograms for the Playmaster taken with various types of resistive and inductive loads, including 30ft of speaker leads, show no suggestion of critical ringing.

On the other hand, at least, one of the commercial amplifiers was obviously not safe in this regard, for the long speaker lead capacitance was enough to make it oscillate under operating conditions.

The more feedback used, the greater the risk of oscillation and the greater is the sensitivity of the amplifier to critical loading. The idea of a 6 db stability margin on speaker load is acceptable, but there is no reason why this figure should have a particular significance.

It is much better to restrict feedback to about 20 db, at which figure most of its advantages are realised, than to risk instability by a design which shows a tendency to ringing or oscillation on any normal load.

A second version of the 17-watt amplifier using a different set of transformers from those illustrated last month.

Amplifier Response & Stability—Part Two

This article continues discussion of Amplifier performance, including the results of tests made with practical designs. It includes a suggested form of layout suitable for most push-pull amplifiers of several sizes using the 17 watt circuits as an illustration.

by John Moyle

LAST month, the importance of the output transformer in setting amplifier performance was considered in some detail with particular reference to high frequency stability.

Four commercial amplifiers were analysed with the aid of photographs taken from the screen of a cathode ray oscillograph, and the same tests were made with the 17-watt ultra-linear amplifier which has proved so popular among our readers.

In this article, some further points on transformer behaviour are discussed with a view to illustrating what happens in some practical designs when feedback and phase correction methods are used.

As was pointed out last month, the application of feedback from the voice coil to the input circuit of an amplifier will reveal peaks in transformer response which are not normally observable without feedback.

These peaks, or even discontinuities in response not large enough to be graced with such a description, can cause phase changes in the amplifier so that the voltage fed back to the input is no longer negative but positive, under which conditions it can produce oscillation or near oscillation, and will do so if the feedback is sufficient and correction is not applied.

Even if it is, oscillation dangers, at both high and low frequencies, are the limiting factors in deciding how much feedback can be applied in a given design.

It was pointed out that, if the transformer resonances are comparatively low down in the response curve, it is almost impossible to deal with them without prejudicing amplifier response even within the audible range.

The best transformers in this regard are those having no more than one major peak, as low in amplitude as possible, and positioned well up in the supersonic region.

The ultra-linear connection of output valves is most valuable in obtaining a clean response and good square wave performance, for it is in effect a local feedback loop applied over the output stage. As such it confers upon the amplifier all the benefits of feedback in reducing distortion and in lowering effective output impedance.

Invariably the behaviour of an amplifier will be improved in almost every particular when the output connection is changed from "pentode" connection to ultra-linear, even when the same transformer is used.

But the general pattern of improving high frequency stability by standard correction methods will apply equally to either connection and by plotting response curves for various operating conditions, it is interesting to see how the results are modified.

The picture becomes even more complete if square wave tests are made at the same time, and we have done this in order to more completely illustrate what takes place.

The first of the curves shows the performance of a better quality output transformer popular a few years ago when connected into the 17-watt amplifier.

Curve 1 shows the response of the amplifier without feedback and speaks for itself. Roll-off commences below 10 Kc and continues steadily thereafter. No resonances are shown on the curve, mainly because the response has fallen so far below reference at frequencies concerned that the are well off the bottom of the graph. The square wave obtained at this time shows the effect of falling high frequency response by its rounded corners, but it also shows some ripples on the contour which are caused by the resonances being excited with the high frequency components of the square wave. Oscillation and ringing can scarcely occur under these conditions.

The second curve on the graph shows what has happened when 20 db of feedback is applied to the amplifier from the voice coil to the input stage.

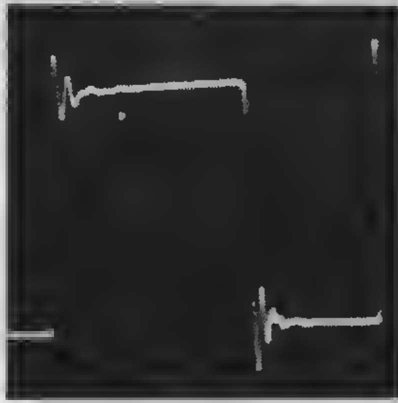
RESONANCE PEAKS

There is a high resonance peak at approximately 120 Kc, a smaller one at 200 Kc and a third at about 75 Kc.

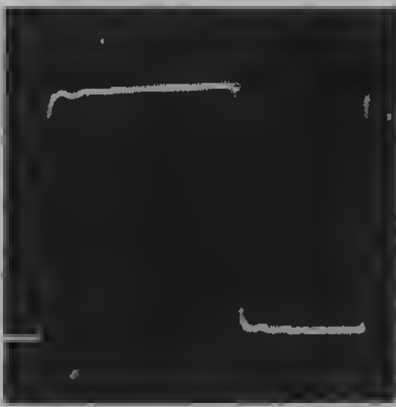
You will notice that, although only 20 db of feedback has been applied, these peaks have risen by much more than this amount. This is because of the regeneration which has taken place in the vicinity of the peak frequencies due to positive-going phase changes in the amplifier, and it is obvious that, with still more feedback, oscillation at the major peak frequency would eventually take

SQUARE WAVE RESPONSE OF PENTODE AMPLIFIER

A 5 Kc square-wave trace of the pentode amplifier without feedback as referred to in this article.



The same amplifier with 20 db of feedback shows pronounced ringing and overshoot.



A capacitor connected across the feedback resistor has materially reduced the ringing and improved stability.

place, although it was not present at this time.

An inspection of the square wave which matches this curve shows just what we would expect—appreciable ringing and overshoot at the high amplitude frequency sufficiently well marked almost to swamp further ringing effects at the other two frequencies, which make their presence known by the irregularities in ringing which appear further along the trace.

By selecting an appropriate value of capacitor across the feedback resistor, we produce curve 3. The drastic modification to the response curve mentioned last month by the addition of this capacitor is clearly shown here, for it has almost wiped the effect of the major peak, and the one above it. There is still a discontinuity in the curve round about 80 Kc, and we would expect to find some evidence of this in the square wave pattern.

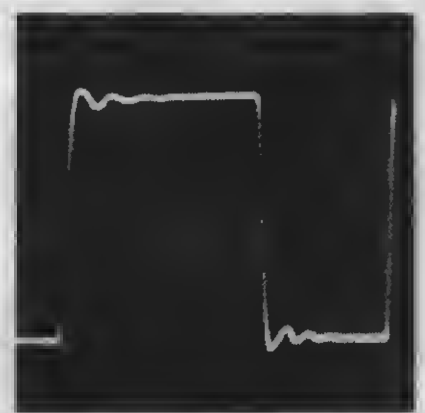
And so we do, the lowered frequency of the small amount of ringing showing quite clearly on the top of the trace. Testing the amplifier with extra feedback and load capacitance demonstrated, too, that its stability had substantially improved.

The final treatment was to introduce a step circuit at the plate of the first valve, the values being somewhat similar to those used in the circuit given last month. The capacitance value selected was that which gave the greatest stability, and in fact the amplifier now would not oscillate with any added capacitance across the load, although values in the vicinity of .05 mfds were the most critical.

EFFECT OF CAPACITANCE

With this capacitance added, the frequency response revealed a very large peak round about 100 Kc, indicating that it had modified the effect of the feedback capacitor to such an extent that the effect of the large resonant peak was once more significant.

The frequency response of the amplifier with the step circuit is shown in curve 4, and it will be seen that the steeper roll-off has accentuated the previous disconuity at about 80 Kc, so that we could expect to find increased ringing at this frequency. The photograph of the square wave trace confirms this, and reference to the previous trace



Addition of a step circuit has accentuated ringing but has further increased stability.

shows that the ringing frequencies in both cases is substantially at the same frequency.

This final adjustment is probably the best that can be done with this amplifier, for the amount of ringing is not severe, although more than one would like, and it is reasonably well damped.

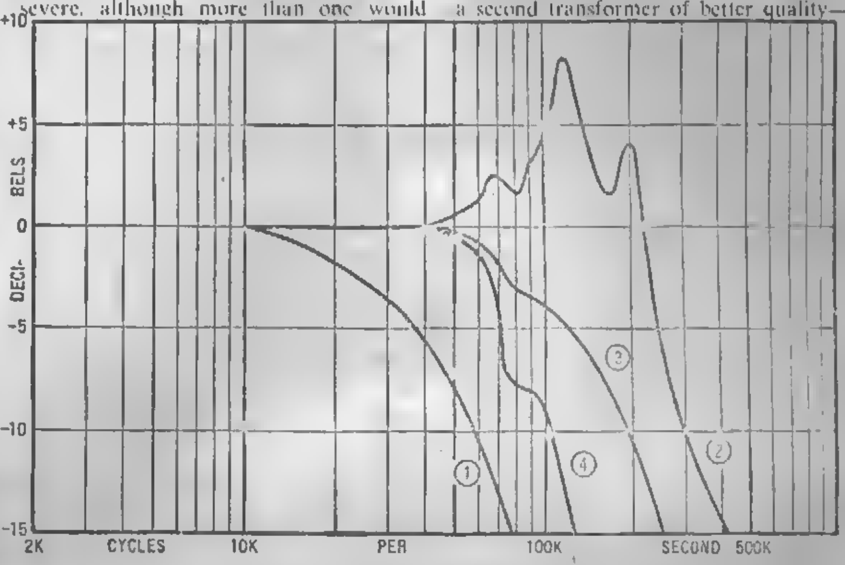
It is obvious that to continue the roll-off process to remove it would mean the attenuation of the upper register sufficiently to reduce the gain at about 80 Kc quite severely, and this could only be accomplished by extending the commencement of roll-off down into the audible range.

The amplifier would still sound quite well, but its specifications could not be considered as being in the upper class.

LIMITED FEEDBACK

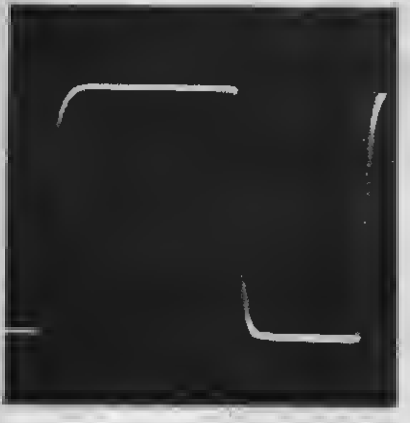
This particular transformer was selected simply because its performance pattern is a particularly clear one. We have used others which exhibited virtually a single resonance peak as low as 50 Kc and of much higher amplitude. It is clear that, with such a transformer, only a limited amount of feedback could be used without danger of oscillation, and that, if the amplifier was adjusted to remove its effects, the final response curve would be far from good, particularly in its response to transients. A rounded corner on the trace would be inevitable.

By contrast, the second curve shows a second transformer of better quality—



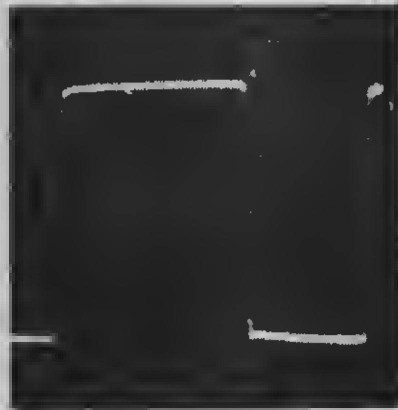
A series of response curves taken from the pentode amplifier referred to and for which square-wave traces are shown above.

SQUARE WAVE RESPONSE OF 17-WATT AMPLIFIER



Square-wave response of the 17-watt ultra-linear amplifier without feedback indicates a good performance.

Application of 20 db of feedback has produced a very small amount of overshoot and no appreciable ringing.



A capacitor across the feedback resistor has virtually removed all traces of abnormality from the square-wave pattern.

an ultra-linear type connected to the same amplifier.

Curve 1 shows its response without feedback, and it is at once obvious that results are going to be noticeably better.

The response is flat to just beyond 20 Kc and a smooth roll-off continues after that point.

The oscillograph trace for this curve shows a rounded front corner, but only on the bottom cycle is there any trace of resonances. This would indicate that resonance frequencies will be high, their amplitude lower than for the first transformer, and that there is a small unbalance which will show them at slightly greater amplitude on the downward stroke of the waveform.

The application of 20 db of feedback bears out this forecast. The curve number 2 shows a main resonance of 200 Kc of appreciably lower amplitude than for the first transformer, with two smaller resonances, one at 100 Kc and another at about 130 Kc. The upper range of the curve crosses reference on its final descent at about 430 Kc, and is only a 4 db down at 500 Kc.

Reference to the square wave pattern shows very slight ringing and overshoot at the commencement of the flat top, with almost immediate damping. As predicted, the overshoot is greatest at the bottom, indicating a small unbalance, probably the reason why it is not so noticeable at the top corner.

COULD BE UNSTABLE

We would expect this condition to be stable in ordinary use, but susceptible to oscillation with critical capacitances across the load.

The third curve shows modification of the response with a capacitor of 50 pf across the feedback resistor. This small value has suppressed the main peak by about 8 db and smoothed out the effect of the others. It appears that the capacitor value is somewhat below optimum. No oscillogram was taken for this curve.

Curve number 4 was taken with the feedback capacitor increased to 100 pf. This has smoothed the lower frequency peaks almost completely out so that they are difficult to trace by the response curve, and reduced the main peak to a notch at 200 Kc. We would, therefore, expect to find a very small residue of the over-shoot pip we saw on the previous oscillogram, and an otherwise clean flat top, for the curve is substantially smooth up to this point.

A step circuit has increased stability and had little effect on ringing, only just discernible at the bottom corner.

Reference to the oscillogram once again bears out anticipations. The overshoot has virtually disappeared from the top of the trace, and can only just be discerned at the bottom, where it has always been most apparent.

The final curve was taken with the step circuit added to the plate of the first valve. The attenuation it represents was enough to reduce the slope of the roll-off to about 6 db per octave, and to remove the final discontinuity to a point where only the most scrupulous plotting of a curve could reveal it. Its minor nature is illustrated by reference to the final oscillograph, where a very slight increase in overshoot can be detected at the bottom of the trace.

GOOD STABILITY

In ordinary use, the amplifier was perfectly stable at this point, and could only be induced to show some ringing and oscillation over a narrow band when a critical capacitance of about .03 mfds was connected across the load. This connection introduced a peak in the response curve at about 200 Kc where it might be expected, but as such a capacitance is not found in any other type of load, it is of no significance in practice. As shown in the oscillograms in last

These curves show the frequency response of the ultra-linear amplifier as detailed on this page.

month's article, the square wave characteristics were virtually unaltered whether the load was 2 or 15 ohms resistive, a loud speaker of 15 ohms, or a cross-over network intended for three-speaker operation.

Only with certain values of deliberately added capacitance could any ringing be introduced to the trace.

The improvement to the performance of the amplifier, therefore, by the use of a high quality transformer in which resonances are controlled far into the supersonic region is clearly demonstrated by a comparison between these two transformers.

EXTRA FEEDBACK

The addition of extra feedback did not alter the general high frequency characteristics to any noticeable degree, even when it was increased to over 30 db, nor did this have any effect on its stability in this region on any kind of working load.

It does not necessarily follow that such a severe test could be successfully applied to the amplifier with other transformers having less desirable characteristics, however, such as might be the case in the ordinary course of home building.

As mentioned in last month's article, we have for the purposes of this analysis ignored the effect of circuitry on the high frequency performance of amplifiers because of the major part played by the output transformers. It is quite true that, in the extreme upper frequencies we have been considering, circuit capacitance will have some effect. Valves capacitances, the characteristics of various types of phase-changer and so on will modify the results to some degree, and these will be of interest to the specialist designer.

But providing that combinations of good quality are used, they are not likely to seriously modify the general pattern of results as exposed in these experiments.

And with the feedback restricted to 20 or 22 db with all the standard transformers we could collect as being suitable for the amplifier, the stability margin could be considered as more than adequate.

As a matter of interest, an oscillogram showing the overload characteristics of the amplifier at 5 Kc is included. It illustrates the good balance of the amplifier, its linearity up to the clipping point, and the sharp cut-off characteristic of a well-designed circuit with feedback. Because the distortion at overload is obviously severe and sudden, it is good practice to use an amplifier with ample output power so that the overload point it not reached, even on the steepest transients.

SPEAKER LOADS

The curves shown on this page, and which were taken from a book by G. A. Briggs on loudspeakers which has just been published, show that the load presented to the amplifier by either a loudspeaker or a cross-over network do not resemble a pure capacitance in the range between about .02 and .5 mfds, which we have seen is likely to be a critical condition for amplifiers.

At no time in fact does the phase angle curve approach 90 degrees in either direction, which would be necessary for the load to become purely capacitive or inductive.

This is borne out by the square wave oscillographs for different types of loads shown in last month's articles, and referred to earlier in this one, which show no sign of critical reactance effects.

The presence of a resistance or resistive component in series with a load capacitance is most significant in determining its effect on stability.

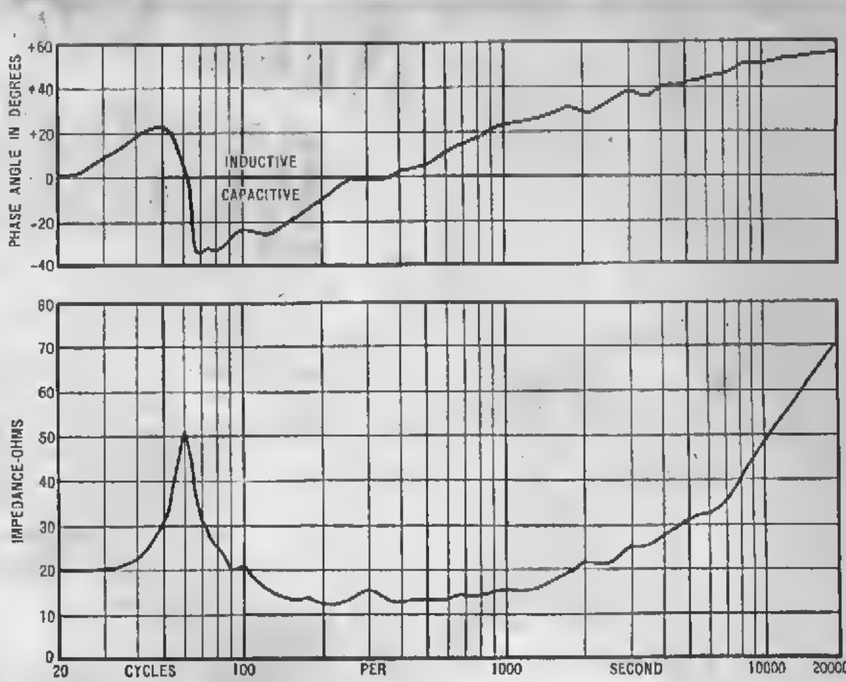
Even with an added critical capacitance, the presence of a few ohms series resistance will reduce ringing and prevent oscillation.

The curves show that a well-adjusted cross-over network is likely to be more stable than a single speaker, as it resembles much more closely the ideal of a constant resistive load.

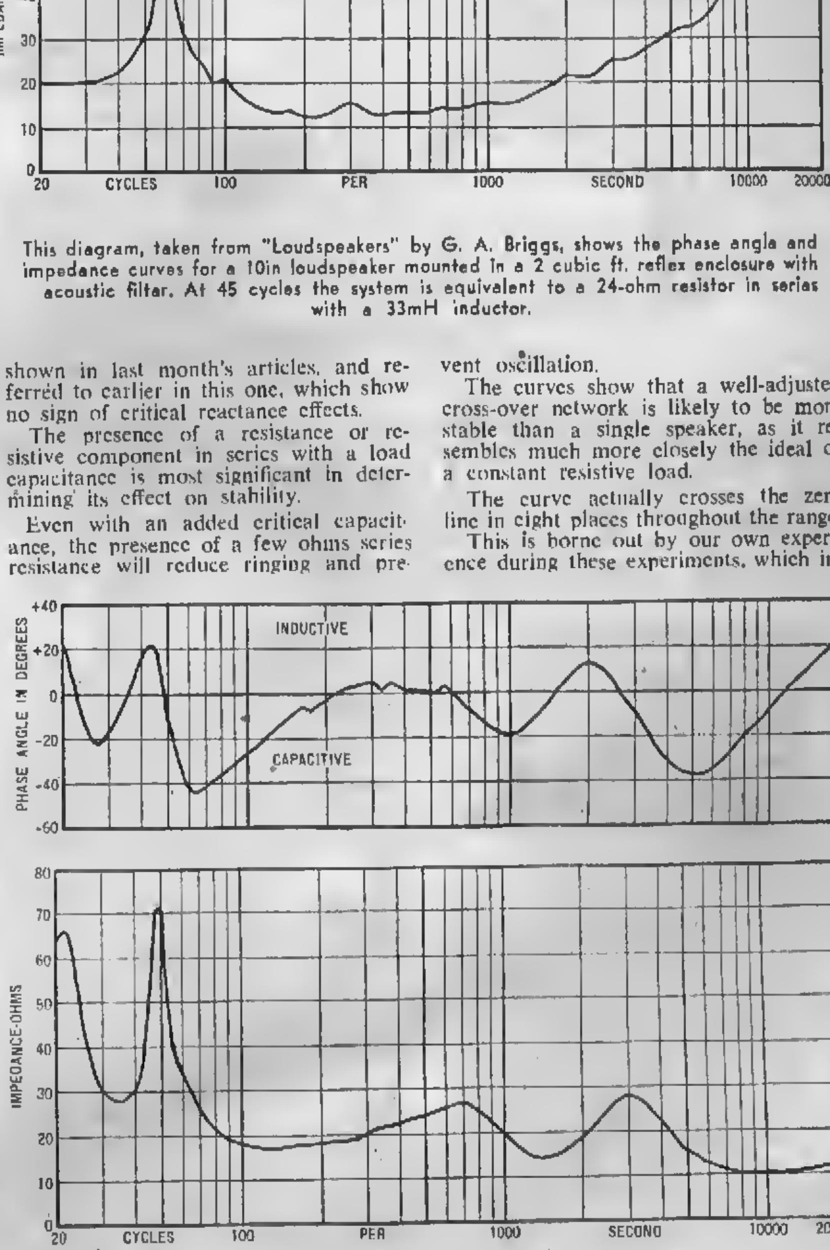
The curve actually crosses the zero line in eight places throughout the range.

This is borne out by our own experience during these experiments, which in-

PERFORMANCE CURVES OF SPEAKERS



This diagram, taken from "Loudspeakers" by G. A. Briggs, shows the phase angle and impedance curves for a 10in loudspeaker mounted in a 2 cubic ft. reflex enclosure with acoustic filter. At 45 cycles the system is equivalent to a 24-ohm resistor in series with a 33mH inductor.



These curves show the behaviour of a 3-speaker reflex system with cross-over network. The load is most predominantly resistive—the curve crosses the zero line in eight places. Note the impedance curve which is almost flat above 60 cycles.

dicated stability under critical conditions very little inferior to that of a pure resistance.

Instability in the frequency range from about 30 cycles to 10 or 20 Kc does not normally occur in amplifiers, because any design worthy of the name has a fairly flat response in that region, and the input and feedback voltages will remain substantially in correct phase.

But there are several factors which can contribute to low frequency instability, or motor-boating, as it is popularly called.

A full treatment of amplifier behaviour with feedback can become quite involved, as illustrated by the vast amount of technical writing on the subject. What happens may be summarised as follows:

PHASE CHANGES

As far as the output transformer is concerned, there are no resonance peaks similar to those which occur in the high frequency region, but at frequencies low enough for the various reactive components in the amplifier to cause phase changes, oscillation due to positive feedback becomes possible, and instability can result.

These phase changes occur in the output transformer itself at frequencies where the inductance of the windings is not adequate to maintain constant amplification.

They will also occur due to the presence of coupling and bypass capacitors at frequencies where the reactance of these components becomes an appreciable number of ohms.

The power supply, which is common to all circuits, will also be responsible for phase changes at extremely low frequencies, for even the largest filter capacitors will have reactance values equal to hundreds of ohms at frequencies approaching zero.

The net result is, that, particularly when feedback is applied, the amplifier frequency response will exhibit a peak in the region of a few cycles per second, and this peak is to be seen in all such curves which have been published from time to time. It is the result of cumulative regeneration, and while its presence does not automatically indicate instability, oscillation is almost inevitable if the degree of feedback is sufficient.

It is not easy to illustrate amplifier performance at low frequencies by curves and oscillograms, for the equipment needed must be capable of operating efficiently down to zero frequency, and is not normally found outside the laboratory.

CIRCUIT TREATMENT

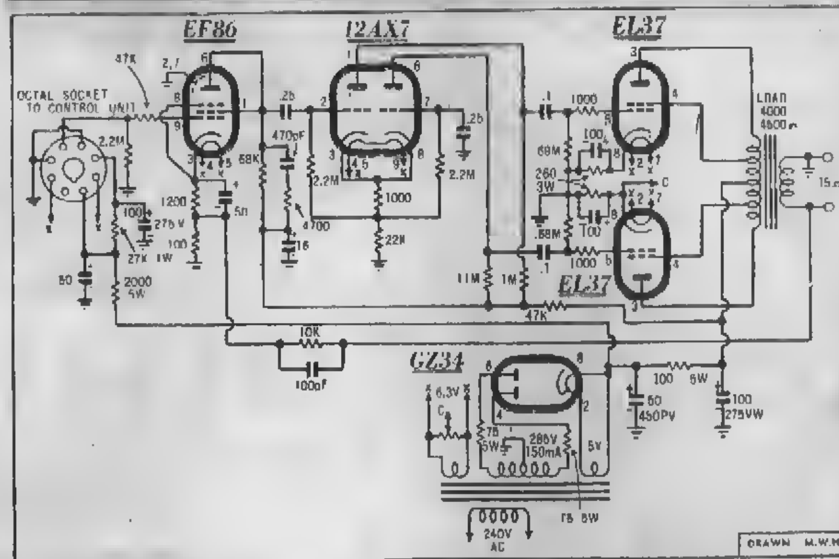
But if the fundamentals of the matter are borne in mind, it is possible to demonstrate various treatments and to observe their effect on a given design.

In practical cases, these treatments divide into two main categories—those concerned with low frequency response in the various stages, and those concerned with power supply coupling.

With optimum circuit values and good transformers, low frequency instability is not usually a problem with 20 db of feedback. This has been demonstrated with the 17-watt amplifier using the circuit values as published.

By restricting feedback to this figure, coupling and bypass capacitors and even output circuit balance are not particularly critical and the design is thereby simplified.

VERY HIGH STABILITY CIRCUIT



The 17-watt circuit showing addition of a step circuit and larger capacitors. Neither is essential for complete stability on any type of normal load, even with long speaker leads.

If the feedback is increased to amounts more than about 26db, however, more care will probably be required, and some designs show evidence of this.

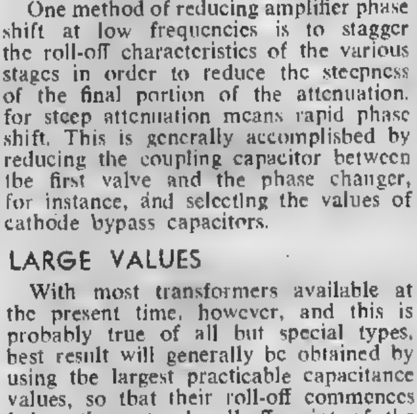
One method of reducing amplifier phase shift at low frequencies is to stagger the roll-off characteristics of the various stages in order to reduce the steepness of the final portion of the attenuation, for steep attenuation means rapid phase shift. This is generally accomplished by reducing the coupling capacitor between the first valve and the phase changer, for instance, and selecting the values of cathode bypass capacitors.

LARGE VALUES

With most transformers available at the present time, however, and this is probably true of all but special types, best result will generally be obtained by using the largest practicable capacitance values, so that their roll-off commences below the natural roll-off point of the transformer.

This was illustrated by increasing the feedback on the 17-watt amplifier until motorboating at a very low frequency could just be induced.

Stability was restored by increasing the value of the coupling capacitor from the EF86 plate to .25 mfds, and by using



Overload characteristics of the 17-watt amplifier at 5 Kc.

the same value for the capacitor which earths the grid of the phase-changer. No improvement was noticed by increasing the coupling capacitor values in the grid circuits of the output valves.

If such high feedback were to be considered, it is probable that balancing the output valves for plate current and input voltages would effect still further improvement, as such severe operating conditions would involve the regulation of the power supply. Separate bias circuits for these valves would also be advisable, as the balancing of this stage becomes progressively important as the stability margin is reduced.

Even without these additional changes, it was possible to apply a sudden switching transient sufficiently large to momentarily paralyse the amplifier, and to see it return to normal operation after two or three cycles of slow oscillation.

With the normal feedback of 20-22 db however, no instability of any kind could be produced.

DIRECT COUPLING

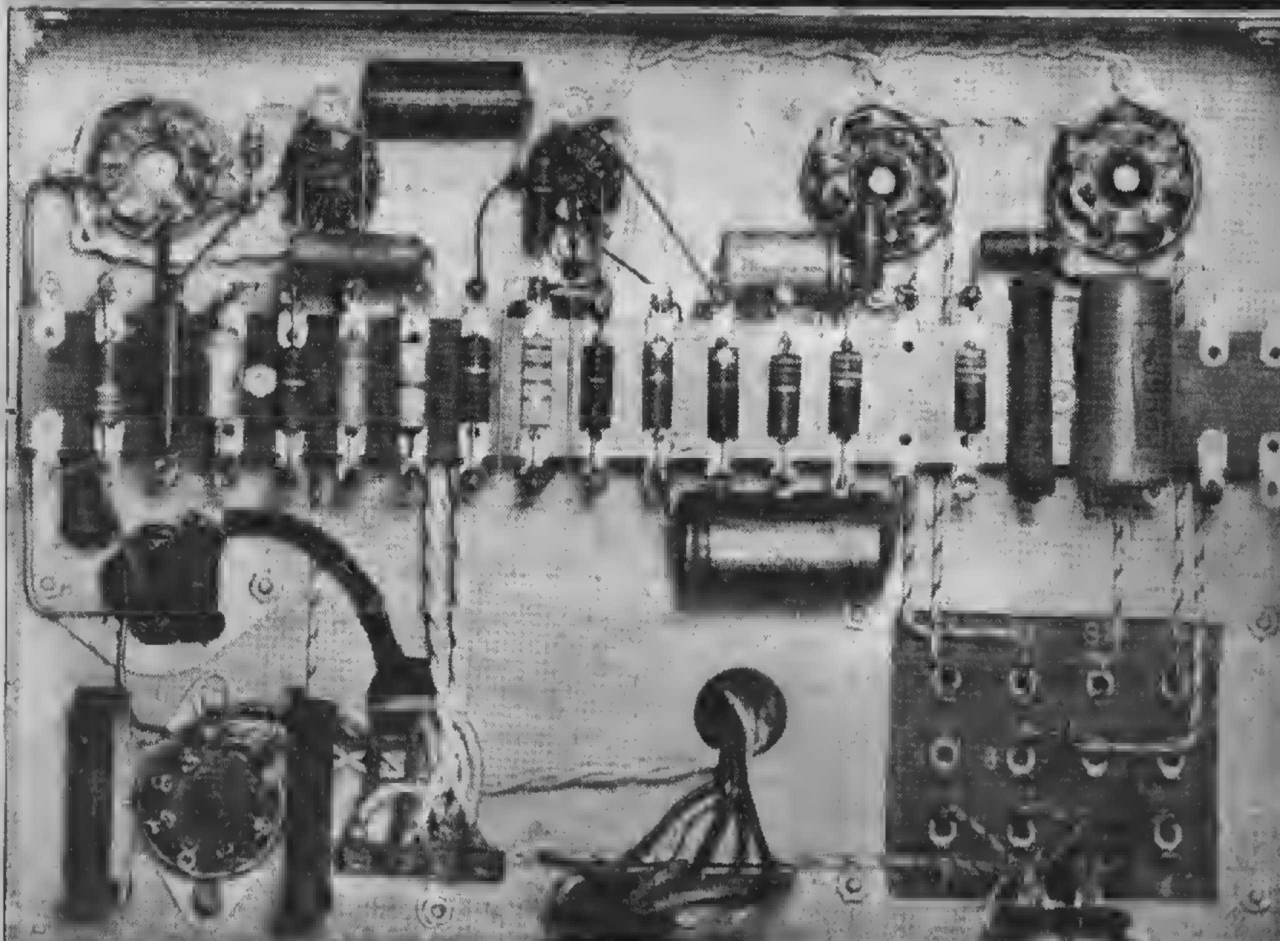
With the aim of reducing one source of amplifier phase change, some circuits use direct coupling between the first valve and the phase changer, but because the stages are still coupled appreciably through the power supply at frequencies of a few cycles per second, this is not as successful as might appear at first sight. It has the disadvantage of reducing the effective voltage applied to the valves concerned, and thus limiting their voltage output which, in the case of the phase changer at least, could be an important point.

Because the power supply is one portion of the amplifier which is common to all circuits, and in most cases to the control unit as well, special consideration must be paid to it.

Best stability will be obtained when the total impedance of the supply is kept as low as possible, which means the reduction of common DC resistance and the use of high-value filter capacitors.

In the 17-watt amplifier, a 100 resistance is used in place of the original filter

UNDER-CHASSIS VIEW SHOWS USE OF COMPONENT STRIP



Under-chassis photograph of the 17-watt amplifier showing the use of a component board. Twin 50 and 100 mfd electrolytics are used, but single tubular units could be substituted. The input socket is at top left.

choke which had a resistance of several hundred ohms, and a total of 150 mfds smoothing capacitance. The rectifier is of a low-resistance type, to reduce this form of coupling to a minimum.

A very considerable increase in stability results from feeding the control unit high tension directly from the rectifier, so that the main resistance-capacitance filter is not included in its feed circuit. Two resistors and 150 mfds of capacitance serve to isolate the control unit still further from possible variations in the amplifier power supply, and this procedure provides stability equal to that achieved by using a separate power supply for the control unit.

With any of the control units described for the Playmaster amplifiers, it is possible to set the gain control and extra bass boost control to their respective maximums, and to feed any kind of signal into the unit up to overload point with no evidence at all of low frequency instability.

Feedback can be increased very appreciably with the controls set in this unrealistic position with the same result.

So far in this discussion of amplifier response we have considered the type of waveform which goes in and compared it with what comes out, with no reference to the waveform which passes through the amplifier from stage to stage. It is obvious that, if the output wave-

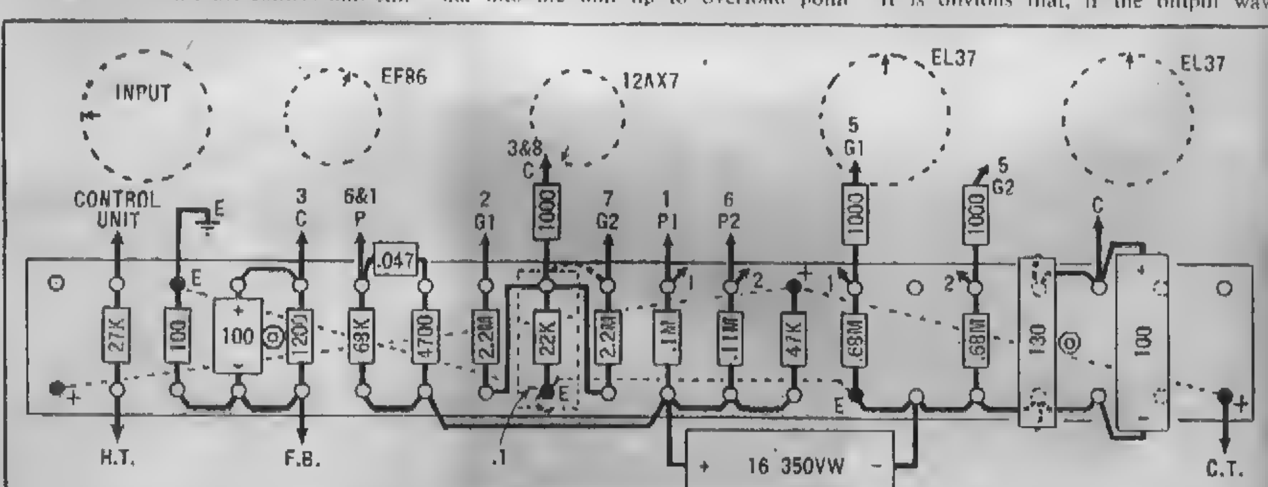
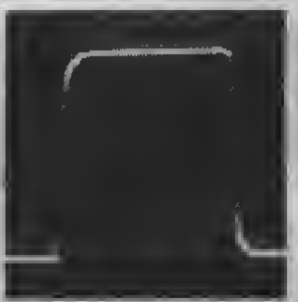
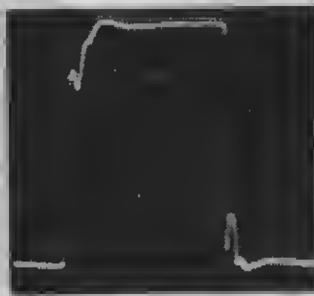


Diagram showing the placement of components on the instrument board.

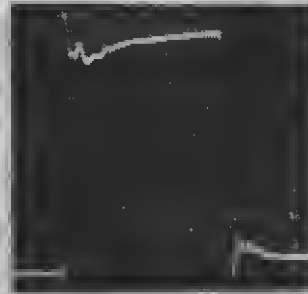
Waveform at plate of EF86. Note large spikes caused by regeneration at transformer resonance.



Waveform at EF86 cathode has notches at corners indicating reduced feedback at resonant frequency.



Waveform at plate of first 12AX7 shows pattern largely reciprocal of that at EF86 plate.



Waveform at plate of second 12AX7 shows the effect of phase reversal in the phase changer.

form is virtually identical with that found at the input, and if we know that the fundamental response of the amplifier is replete with peaks and phase changes, there will be a procession of complimentary but distorted waveforms within the amplifier.

It is interesting to note what these might be, and whether there are any dangers inherent in their presence.

Shown on this page are a procession of waveform photographs obtained by feeding a 5 Kc square wave into the amplifier and connecting the oscilloscope to various points. In order to show the various effects more clearly, a version of the 17-watt amplifier was denuded of all compensation circuits, and operated with 20 db of feedback.

The first trace was taken from the plate of the EF86. The interesting thing to note here is the very high spike at the commencement of the trace.

This spike represents the frequency of the main transformer resonance at about 100 Kc as revealed in the response curve shown on page 33. By increasing the frequency of the oscillator, this frequency was found to be the one which lined up with the spike.

CROSS CHECK

A further check was made by observing the frequency response of the amplifier as read at this check point, and a very large peak was observed in the response at that point.

It is obvious that, if program were to be fed to the amplifier with components which could excite it at this frequency, the phase-changer would be in danger of overload at higher levels.

In practice this is not likely to occur, as input voltages of sufficient amplitude at this frequency would be most unusual. But it is a most significant point in understanding the operation of an amplifier, and underlines the dangerous effects of regeneration at these peak frequencies. In this case, the amplifier could probably be shocked into oscillation if the feedback were slightly increased.

The next waveform shows the waveform as read at the EF86 cathode. The sharp notch on the leading corner is what we would expect to see with a decrease in negative feedback in this region, and this is what happens through the presence of the transformer peak. This waveform is not purely a represensation of the feedback voltage—it is modified by the operation of the EF86 —but the pattern is there.

AT THE PHASE-CHANGER

The third trace is taken at the plate circuit of the first 12AX7 section. It is to a large extent a reciprocal of the trace at the EF86 plate, for it has undergone a phase change through the triode, and instead of spikes on the leading edge we find complementary notches in the pattern. Note again that the trace is not symmetrical, indicating unbalance in the output transformer which initiates the voltages which are modifying the original square wave.

The fourth trace is taken at the plate of the second 12AX7 section. Here a further phase change has taken place, so that we see a modified form of the trace at the EF86 plate.

The spikes here are very much reduced in amplitude. This could be due to a clipping action of the valve sections as we would expect if the input was high enough to overload them, but more probably because of the falling frequency response of this part of the circuit at the 100 Kc frequency. Note again that the balance is not perfect.

The next two traces were taken at the plates of the output valves and here we see the general shape of the two wave-forms which, combined in the output circuit, make up the wave-form as seen by the loudspeaker. Again it will be noticed that there is an unbalance between the two sides of the circuit and their imperfect cancellation might be expected to leave some ringing pattern in the output. This is confirmed by the next trace which shows a small amount of unbalanced ringing. It was taken from the output terminals of the amplifier.

Both these wave-forms are affected by the close connection of the valves to the transformer, and to each other through the transformer. Thus they are not completely representational of the contribution each valve makes individually to the circuit.

As a matter of interest, compensation was restored to the amplifier, and the last two traces photographed. The first shows the EF86 plate circuit again, with the spikes very much modified, due to the suppression of the resonance effects in the transformer. The second is the trace at the output terminals, again showing a considerable cleaner, and quite good wave-form.

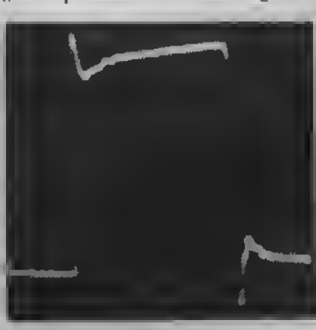
DISTORTION DANGER

Some of these wave-forms show malformation of the flat top extending almost halfway along it, and would, therefore, concern frequencies quite close to the top of the useful audio range. It could be argued that intermodulation products might be expected if resulting non-linear effects were to fall within the band, or if bias shifts were to take place at high amplitudes which could originate such distortions.

At any rate, it is clear, as emerged from earlier discussions, that transformers with very high frequency peaks of low amplitude which can be nullified

(Continued on Page 127)

Waveform at plate of one EL37 output valve.



Waveform at plate of second EL37.

Waveform at plate of circuit of EF86 with compensation.

Waveform at output of amplifier with compensation.

AMPLIFIER RESPONSE AND STABILITY

(Continued from page 41)

by compensation circuits that do not affect the response for some distance beyond the usable frequency range must be preferred, not only because of their possible superiority in frequency response and low distortion, but in the interests of achieving the highest standard of stability.

As promised in an earlier issue, we are including with this article a layout for a component strip which may be wired up as a unit, and which supports nearly all resistors and capacitors.

The strip is mounted on two long 1/8in bolts which run through the top of the chassis.

Underneath the strip, and therefore not shown, are leads connecting together three high tension and three earth points.

The high tension lead is connected to a lug at the extreme right-hand end of strip, continues across to the end of the 47K decoupling resistor, and thence to a lug at the extreme right hand end of the strip where it makes a convenient point to connect the centre tap of the output transformer primary.

The earth lead is connected to the end of the 100 ohm resistor in the EF86 cathode, thence to the earthed end of the 22K resistor in the cathode circuit of the 12AX7, and finally to the earthy end of a .68K grid resistor for the EL37.

These hidden leads are connected to the lugs by soldering through the eyelet holes.

The whole strip may be pre-assembled, and then wired into place.

The feedback resistor and capacitor are wired to pins on the four-pin socket used for loud speaker connection.

This lead is earthed to the chassis at only one point, near the EF86 valve, to which point is earthed the EF86 grid resistor and the earthed connections from the control unit.

The grid coupling capacitors for the EL37s are not drawn in the diagram, but their connecting points are clearly indicated by small numbered arrows. One of them is tucked under the strip, but the other can be seen in the photograph.

The capacitor which earths one grid of the 12AX7 is also tucked under the strip and is earthed to the appropriate end of the 22K resistor in the cathode circuit of this valve.

The strip is connected to the valve sockets by short, direct leads.